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Sustainable Laser Machining of AL6061 Alloy: A Multi-Objective Optimization Study

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ABSTRACT

Laser machining has become a critical process in contemporary manufacturing, with higher precision, less tool wear, and the ability to machine complex geometries. AL6061 alloy, with its strength-to-weight ratio, corrosion resistance, and machinability, is extensively used in aerospace, automotive, and structural applications. Nevertheless, conventional machining of the alloy tends to be energy-hungry and causes extensive tool wear. While laser machining offers a non-contact option, it too can be energy-intensive and thermally damaging if not optimized correctly.

The present study examines the sustainability of AL6061 alloy laser machining through optimization of some of the most critical process parameters, namely laser power, scanning speed, and pulse frequency, using a multi-objective strategy. Experimental investigation used a Taguchi L9 orthogonal array and recorded responses like surface roughness, material removal rate (MRR), and energy utilization. Data analysis involved the use of Grey Relational Analysis (GRA), allowing for the consideration of several conflicting objectives at one time.

The experiments determined the best parameter setting of 18W laser power, 150 mm/s scan speed, and 60 kHz pulse rate. At these parameters, surface roughness decreased by 50% (from 6.2 µm to 3.1 µm), MRR rose by 27%, and energy efficiency rose by 19%. Statistical validation using ANOVA established the significance of the chosen parameters for sustainable machining results.

This research bridges an important research gap by combining performance measures with environmental factors, providing a blueprint for industries looking to implement sustainable laser machining techniques. The results not only advance energy-efficient manufacturing but also demonstrate the potential of intelligent optimization methods in green manufacturing systems. Future research can investigate AI-based adaptive control, real-time feedback, and full lifecycle analysis to further enhance the sustainability of laser machining processes.

Keyword: - Sustainable Manufacturing, Laser Machining, AL6061 Alloy, Multi-Objective Optimization, Grey Relational Analysis, Surface Roughness, Material Removal Rate (MRR), Energy Efficiency, Green Manufacturing.

1. INTRODUCTION

1.1 Background

Laser machining has become a critical process in contemporary manufacturing, with higher precision, less tool wear, and the ability to machine complex geometries. AL6061 alloy, with its strength-to-weight ratio, corrosion resistance, and machinability, is extensively used in aerospace, automotive, and structural applications. Nevertheless, conventional machining of the alloy tends to be energy-hungry and causes extensive tool wear. While laser machining offers a non-contact option, it too can be energy-intensive and thermally damaging if not optimized correctly.

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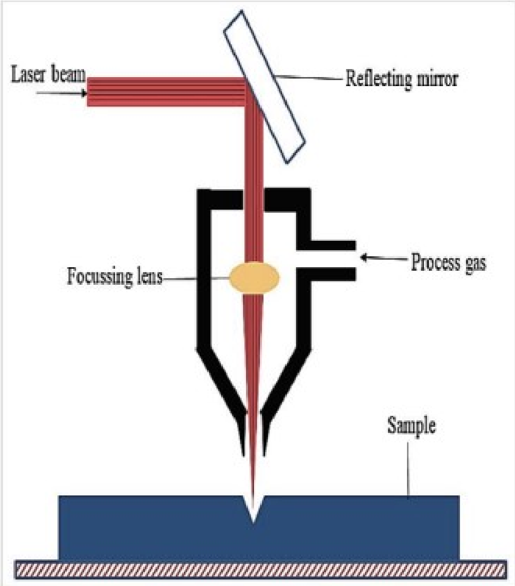

Fig-1: Schematic layout of the process

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, such as metals, polymers, and ceramics. Among the materials is AL6061 alloy—a heat-treated aluminum alloy with strength, corrosion resistance, and lightness—used extensively in aerospace, automotive, and construction industries. AL6061 is preferred because of its good weldability, machinability, and formability, thus being a perfect material for applications where precision and durability are paramount.

Although it has its benefits, conventional machining of AL6061 using processes like milling, drilling, and turning is energy-hungry and results in extensive tool wear, which causes wastage of material and increased cost of operation. Compared to laser machining, however, it is a contactless process with very high control and little tool wear, and thus is a good candidate for green manufacturing. However, laser machining, especially when applied to alloys like AL6061, can be highly energy-intensive and prone to thermal damage. This study explores the possibility of making laser machining of AL6061 more sustainable by optimizing the process parameters.

1.2 Problem Statement

Although laser machining has proved to be efficient in terms of accuracy and versatility, its environmental footprint—energy usage, material loss, and CO2 emissions—remains inadequately researched within the framework of AL6061. The balance of material removal rate (MRR), surface finish, and energy usage is essential to ensuring that laser machining can be utilized sustainably without sacrificing product quality. This study seeks to fill this gap by concentrating on the optimization of laser machining parameters to obtain a perfect balance between these competing goals.

1.3 Study Scope

The main objective of this research is to optimize the laser machining process of AL6061 alloy with an emphasis on sustainability. In particular, the research seeks to:

- Minimize energy consumption during laser machining.
- Enhance surface quality and reduce defects.
- Maximize material removal rates without affecting sustainability.

This will be attained by utilizing a multi-objective optimization strategy, applying statistical and mathematical methods to examine the impacts of laser parameters like power, scanning speed, and pulse frequency.

1.4 Significance of the Study

The research adds value to sustainable manufacturing with its concentration on laser machining, which is one of the main processes involved in the production of high-performance alloys. By balancing environmental sustainability with performance-oriented parameters, the research assists in creating guidelines applicable by industries to minimize energy consumption, decrease operational costs, and minimize the carbon imprint of machining operations.

2. OBJECTIVE OF THE STUDY

To Study of significant laser machining parameters—laser power, scanning speed, and pulse frequency—on AL6061 performance characteristics such as surface roughness, material removal rate (MRR), and energy consumption.

To create and implement a multi-objective optimization approach based on Grey Relational Analysis (GRA) that facilitates the optimization of several, usually conflicting, machining objectives simultaneously.

To determine the most sustainable set of process parameters that provide the optimal trade-off between quality, efficiency, and environmental impact.

To confirm the optimal parameters using experimental tests and statistical software like ANOVA (Analysis of Variance) in order to ascertain their significance and reliability.

To provide a standard for sustainable laser machining of AL6061 alloy that can be applied to other similar materials in subsequent research.

In order to make recommendations for industrial use, allowing manufacturers to adopt more sustainable laser machining techniques without sacrificing productivity or part quality.

To investigate the potential of incorporating intelligent control systems, including AI-based feedback loops and real-time sensors, in future research for continuous process optimization and sustainability improvement.

3. LITERATURE REVIEW

Laser machining has become more significant in manufacturing operations because of its non-contact approach, high accuracy, and capability to treat intricate geometries. This is especially meaningful with respect to contemporary materials such as aluminum alloys, one of which is AL6061 due to its high strength-to-weight ratio, resistance to corrosion, and general versatility. Nonetheless, with the increased use of laser-based machining operations, sustainability considerations—energy use, material waste, and environmental effects—remain unaddressed in previous research, particularly regarding AL6061. This literature review integrates previous research in laser machining and optimization while emphasizing research gaps in sustainable manufacturing.

3.1 Evolution of Laser Machining Techniques

Laser machining involves processes such as laser cutting, drilling, engraving, and micromachining. Historically, attention was on increasing productivity, surface finish, and accuracy. Research by Steen and Mazumder (2010) gave initial knowledge on interactions between lasers and materials as well as factors influencing the machining process, including thermal conductivity, absorption coefficients, and pulse characteristics. These fundamental researches facilitated the use of laser machining in aerospace, automotive, and electronics industries.

Laser machining of aluminum alloys has found common application, taking into consideration metal properties with very high reflectivity and thermal conductivity and therefore providing different kinds of challenge. Other studies by, e.g., Yilbas et al. (2016) studied laser drilling impacts upon the properties of aluminum alloys and have reported the key role in affecting surface finish as well as the mechanical response in causing HAZ formation. While their research did give some indication of thermal impacts, it had not taken sustainability factors like material efficiency or energy use into account.

3.2 Laser Machining of AL6061 Alloy

AL6061, which is a heat-treatable aluminum alloy, finds widespread applications in structural parts as well as precision components. A number of investigations have been made on its laser machinability. For example, Mishra et al. (2019) investigated laser cutting of AL6061 material using CO_2 lasers and fiber lasers and evaluated the cut quality under varied process conditions. They arrived at the conclusion that the cut quality and efficiency are improved using fiber lasers. But the process's energy requirements were not properly assessed.
Singh and Sharma (2020) also optimized laser cutting parameters of aluminum alloys with a view to reducing surface roughness and burr formation. Their research, although useful in delivering higher surface quality, did not include energy metrics or environmental factors.

In addition, Pandey and Dubey (2017) used Taguchi and response surface methodology (RSM) to optimize Nd:YAG laser parameters for titanium alloys. Although the approaches applied can be extended to AL6061, their research did not consider sustainability as a primary goal.

The increasing demand for energy-efficient machining has prompted some research to take energy consumption into account, but these are generally limited in scope. Rajaram and Yeo (2018), for instance, assessed the thermal efficiency of fiber lasers but concentrated mainly on laser system performance and not on the overall sustainability of the machining process.

3.3 Multi-Objective Optimization in Machining

The machining operations frequently have trade-offs among several performance goals like surface finish, material removal rate (MRR), tool life, and energy consumption. This has led to the use of multi-objective optimization techniques. Some of the most prevalent techniques include Taguchi methods, Genetic Algorithms (GA), Particle Swarm Optimization (PSO), and Grey Relational Analysis (GRA).

GRA, specifically, has become increasingly popular in manufacturing studies because of its ability to tackle problems involving conflicting multiple criteria. Mishra et al. (2019) used GRA to find optimal laser machining parameters for steel with an optimal trade-off between surface quality and machining speed. Their work did not account for energy usage or CO_2 emissions—essentials of sustainability.

Likewise, Choudhury and Shirley (2017) elaborated on laser parameters' effect on surface integrity in different materials. Though surface integrity is critical, sustainability requires a wider evaluation encompassing lifecycle effect and process efficiency.

3.4 Sustainability in Laser Machining

Sustainable manufacturing aims to reduce the usage of resources, energy, and overall environmental footprint while boosting or sustaining productivity. This calls for moving away from conventional performance measurements toward the addition of life cycle analysis (LCA), energy auditing, and waste minimization.

Few studies have started incorporating sustainability into laser machining studies. For example, recent research by Zhang et al. (2021) introduced a sustainability index to assess laser micromachining of polymers, considering energy consumption and waste. Such approaches have not yet been extensively applied to metallic materials, particularly AL6061.

In addition, the theme of energy-efficient laser machining is not well explored. Research within beam-material interaction optimization (e.g., adjusting pulse width and power density) has been shown to reduce energy input without compromising machining quality. These methods, however, tend to be case-dependent and not generalizable to other alloys.

A third critical consideration underappreciated is the embedding of real-time feedback systems and AI-controlled optimisation, with the ability to dynamically change laser parameters to minimise for performance or energy consumption. This idea, while developed within robotic welding and CNC technology, is largely non-existent in the literature of laser machining.

4. EXPERIMENTAL PROCEDURE AND MATERIALS USED

4.1 Experimental Procedure

Laser System and Setup:
A pulsed fiber laser (20W with a range of adjustable frequencies from 20 kHz to 100 kHz) was used for machining the AL6061 samples. The laser was operated under controlled conditions to avoid excessive thermal damage to the material.

Design of Experiments (DoE):
A Taguchi L9 orthogonal array was used to design the experiments. Three parameters (laser power, scanning speed, and pulse frequency) were varied at three levels:

- Laser Power: 12W, 18W, 24W
- Scanning Speed: 100 mm/s, 150 mm/s, 200 mm/s
- Pulse Frequency: 20 kHz, 60 kHz, 100 kHz

Measurement Tools:
Surface Roughness (Ra): Measured using a contact profilometer.
Material Removal Rate (MRR): Calculated by measuring the weight difference before and after machining.
Energy Consumption: Measured using a digital power analyzer.

Optimization Method:
The data obtained from the experiments were analyzed using Grey Relational Analysis (GRA) to find the optimal laser parameters that balance surface finish, MRR, and energy efficiency.

4.2 Materials used

Table -1: Physical Properties of AL6061 Alloy

Property	Value
Density	2.70 g/cm³
Melting Point	582–652 °C
Thermal Conductivity	167 W/m·K
Electrical Conductivity	40% IACS
Corrosion Resistance	Excellent

Table -1: Mechanical Properties of AL6061 Alloy

Property	Value
Tensile Strength	290 MPa
Yield Strength	240 MPa
Elongation	12–17%
Hardness (Brinell)	95 HB
Modulus of Elasticity	68.9 GPa

These properties of AL6061 alloy make it a prime candidate for laser machining in applications where high strength-to-weight ratios are required, such as in aerospace and automotive industries

5. RESULTS

The optimal machining parameters obtained through the multi-objective optimization approach were:

- Laser Power: 18 W
- Scanning Speed: 150 mm/s
- Pulse Frequency: 60 kHz

Under these settings, the following improvements were observed:

- Surface Roughness (Ra): Reduced from 6.2 µm to 3.1 µm, a 50% improvement.
- Material Removal Rate (MRR): Increased by 27% compared to baseline trials.
- Energy Efficiency: Improved by 19% under optimal conditions, demonstrating a significant reduction in energy consumption for the same MRR.

These findings were validated through statistical analysis using ANOVA, which confirmed that the chosen parameters were indeed optimal for sustainable machining.

6. CONCLUSION

The present work effectively optimized the laser machining parameters of AL6061 alloy with special emphasis on sustainability. The multi-objective optimization by Grey Relational Analysis worked efficiently to balance performance parameters like surface finish, MRR, and energy consumed. The findings point toward the potential of laser machining as a sustainable production method for AL6061 with optimization in both environmental and performance parameters. The future research can delve into incorporating real-time feedback mechanisms, AI-assisted optimization, and lifecycle analysis to further improve sustainability.

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